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ROTORCRAFT TRANSMISSIONS

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SUMMARY

The NASA Lewis Research Center and the U.S. Army Aviation Systems Command share an interest in advancing the technology for helicopter propulsion systems. In particular, this paper presents highlights from that portion of the program in drive train technology and the related mechanical components. The major goals of the program are to increase life, reliability, and maintainability, to reduce weight, noise, and vibration, and to maintain the relatively high mechanical efficiency of the gear train. The current activity emphasizes noise reduction technology and analytical code development followed by experimental verification. Selected significant advances in technology for transmissions are reviewed, including advanced configurations and new analytical tools. Finally, the plan for transmission research in the future is presented.

INTRODUCTION

Since 1970 the NASA Lewis Research Center and the U.S. Army Aviation Systems Command have shared an interest in advancing the technology for helicopter propulsion systems. The major goals of the program are to increase life, reliability, and maintainability, to reduce weight, noise, and vibration, and to maintain the relatively high mechanical efficiency of the gear train (fig. 1, ref. 1). Highlights from the current research activity are presented next.

ANALYSIS

The current activity emphasizes analytical code development and validation with emphasis on noise reduction technology for drive systems (fig. 2). There is a gear technology effort which supports advances in life, higher power density, and lubrication for gears.

On the basis of experimental, analytical, and design studies conducted under the transmission technology program, some advanced transmission concepts were evolved, including the advanced 500-hp transmission, the bearingless planetary transmission, and the split-torque transmission.

An extensive data base has been established for two sizes of helicopter transmissions. The Army's UH-60 Blackhawk transmission has been run in the Lewis test stand to determine thermal, vibration, stress, and efficiency information for a matrix of operating conditions (ref. 2). This information is

being used to compare with computer code predictions for code validation and to provide a baseline from which to assess the promised advantages of future designs and concepts. Information of a similar nature and purpose was collected for the OH-58 transmission (refs. 3 and 4). The Lewis test stands are currently operational and available for use in experimental transmission work.

The NASA/Army program has produced some very useful computer programs for designing and analyzing rolling element bearings (refs. 5 to 8). Generally, the computer program can predict performance characteristics including Hertz stress, load distribution, lubrication film thickness, component kinematics, fatigue life, heat generation, operating temperature, and power loss as a function of input parameters such as bearing geometry, speed, and load. The programs permit better designs and eliminate much trial-and-error testing prior to selection of a final design.

Analyses and computer codes have also been developed for gears to provide the following types of calculations: (1) power loss and efficiency, (2) bevel gear contact geometry, (3) gear dynamic analysis, (4) weight minimization, (5) life prediction, (6) lubrication, and (7) temperatures.

An in-house and university grant effort continues to develop computer programs for analysis and design of transmission systems. The unique facilities and hardware at Lewis are being used to validate the computer codes and to collect additional data for use in developing the codes. A library of computer codes and subroutines for transmission system analysis is being assembled. The goal is to develop a comprehensive computer program library for transmission system modeling (fig. 3).

GEAR AND TRANSMISSION LIFE

Pitting fatigue is a natural wearout mode of gear failure and occurs even under ideal operating conditions with proper lubrication and stress levels. For each hour of operation there is a reliability level which can be calculated. Early work at NASA provided an analytical methodology for calculating life and reliability for gears by assuming a quasi-static load on the gear teeth (ref. 9). It was desired, therefore, to improve on this methodology by replacing the assumed quasi-static load with a calculated dynamic load in the life and reliability model.

TELSGE, a NASA gear dynamic load prediction program (ref. 10), was modified, a pitting-fatigue-life prediction analysis was added, and parametric studies were performed. The study identified contact ratio and operating speed as the two most influential parameters among those studied (ref. 11). As a result, gear life can be increased through the improved analytical life prediction method.

Drive system life and reliability are important issues during the design, development, and field operation of helicopters. Analytical tools are needed for design and for comparing competing and alternate designs.

To meet this need, a versatile computer program was developed to predict helicopter transmission life (fig. 4, ref. 12). The program can analyze a variety of configurations composed of spiral bevel gears and planetary gears.

The program determines the forces on each bearing and gear for a given transmission configuration and applied load. The life of each bearing and gear is determined. Program output includes component and total system lives and load capacity for a given mission profile. The program predicts mean time between failures (MTBF) and can be used to evaluate proposed new designs and to project spare parts requirements for helicopter fleet operations.

GEAR NOISE

Historically, helicopters have been plagued by internal noise problems. Noise levels range from 100 to 120 dBa in the cabin. The sound can be from many sources, such as the transmission gear noise, the turbine engine compressor and exhaust noise, the rotor blades, and air turbulence. The transmission is a particularly troublesome source and is believed to be the main source of annoying noise in the helicopter cabin. The noise from the transmission enters the cabin following two paths: structure-borne radiation and direct radiation (fig. 5). The magnitude of the direct radiation is a function of the acoustic power radiated from the transmission case, transmitted acoustically to the cabin outer walls, and transferred through to the cabin. Of course if there are any small openings in the wall between the transmission compartment and the cabin, the sound will directly enter the cabin. The structure-borne path is particularly hard to block because the transmission case and its mounts are an integral part of the lift-load bearing path. The transmission mounts must be strong enough to support the entire helicopter by transferring the lift-load from the rotor blades to the air frame, and rigid enough for stable control of the helicopter. The stiff mounts pass the gear vibrations exceedingly well to the airframe, and the sound transmits to the cabin directly.

The major portion of our program in transmissions is devoted to finding solutions to this problem.

Spiral bevel gears are used in helicopters to transmit power "around the corner" from a horizontal engine output shaft to the vertical rotor shaft. Vibration from spiral bevel gears is a strong source of transmission noise (fig. 6, ref. 13).

The goal of a recent study was to relate gear noise to physical factors such as deviations of tooth surfaces and gear shaft centerlines from their ideal positions, tooth and gear body stiffness, bearing and housing support flexibility, and input shaft torque. Equations have been developed for computing the vibration and noise of the gear drive system. The work completed (1) provides the first detailed mathematical understanding of generalized transmission error in spiral bevel gears, (2) allows prediction of vibration excitation based on gear tooth measurements, and (3) relates gear noise to physical design parameters and therefore provides a basis for future improvements in spiral bevel gear design (ref. 14).

ADVANCED TRANSMISSIONS

Advancements in transmissions can come from either improved components or improved designs of the transmission system (fig. 7). The split-torque arrangement is in the second category. The figure shows a split-torque design which is compatible with the Blackhawk (UH-60A) helicopter. The fundamental

concept of the split-torque design is that the power from the engine is divided into two parallel paths prior to recombination on a single gear that drives the output shaft. Studies have shown that replacement of the planetary gear reduction stage with a split torque results in weight savings and increased reliability (ref. 15). There can be many pinions driving the output gear, but in the case of the UH-60A application it was found that four pinions gave the optimum design on the basis of least overall weight, reduced power losses, comparable total parts count compared to the existing UH-60 design, and least number (one) of nonredundant gears. The advantage of split torque over planetary is greatest for the larger sized helicopters.

The engineering analysis showed that the following performance benefits can be achieved for a 3600-hp split-torque transmission compared with the conventional transmission with a planetary gear stage: (1) weight is reduced 15 percent, (2) drive train power losses are reduced by 9 percent, (3) reliability is improved and vulnerability is reduced because of redundant power paths, and (4) the number of noise generation points (gear meshes) is reduced.

The transmission has potential for installation in the Blackhawk helicopter. The design study has carried the transmission to the detail design stage for a test model to be used for validation studies in the NASA Lewis 3000-hp helicopter transmission facility, but a test model has not been built. For the transmission to be used in the Blackhawk, a separate detail design and installation study would be required first.

The design emphasis for the NASA/Bell Helicopter Textron (BHT) 500-hp advanced technology demonstrator transmission was placed on a 500-hp version of the OH-58C, 317-hp transmission that would have a long, quiet life with a minimum increase in the cost, weight, and space that usually increases along with power increases. This was accomplished by implementing advanced technology that has been developed during the last decade and making improvements dictated by field experience (ref. 16).

These advanced technology components, concepts, and improvements, and their effect on the 500-hp transmission are as follows:

(1) High contact ratio planetary gear teeth reduce the noise level and increase life.

(2) Improved spiral bevel gears made of vacuum carburized gear steels, shot peened for increased gear tooth pitting fatigue life, as well as gear tooth bending fatigue strength, and lubricated with Aeroshell 555 oil save weight and space and increase transmission life.

(3) Improved bearings, made of cleaner steels and designed with improved analytical tools, save weight and space and increase reliability.

(4) Improved design of the planet carrier, made of two-piece construction with straddle mounting of the planet gears, improves gear alignment and power capacity.

(5) The cantilever-mounted planetary ring gear has no working spline to generate wear debris; it isolates the meshing teeth from the housing to reduce

noise, and it provides a flexible mount for a more uniform load distribution among the planets.

(6) The sun gear now has an improved spline (crown hobbed and hardened) running submerged in a bath of flowthrough oil, which prevents the spline from wearing.

(7) The straddle-mounted bevel gear allows higher torque to be transmitted without detrimental shifting of the tooth contact pattern.

In summary, the improved 500-hp design has a weight/horsepower ratio of 0.26 lb/hp, compared to 0.37 lb/hp for the 317-hp OH-58C transmission. This transmission is the basis for the transmission in the Army's improved OH-58D model helicopter.

One recent development in the area of high-performance power transmissions is the self-aligning, bearingless planetary (SABP) (ref. 17). This transmission arrangement can be generically classified as a quasi-compound planetary which uses a sun gear, planet spindle assemblies, ring gears, and rolling rings.

The design study projects a weight savings of 17 to 30 percent and a reliability improvement factor of 2:1 over the standard transmission. The benefits of using an SABP transmission are most effective when one uses reduction ratios between 16:1 and 26:1. It permits high reduction in two compound stages of high efficiency, providing sufficient flexibility and self-centering to give good load distribution between planet pinions, while effectively isolating the planetary elements from housing deflections.

This new transmission concept offers advantages over transmissions that use conventional planetary gears: higher reduction ratio, lighter weight, increased reliability, and decreased vulnerability. Since it has no planet bearings, there is a weight savings, and power losses and bearing failures commonly associated with conventional-design transmissions are nonexistent.

In conventional-design transmissions, planet bearings are heavily loaded and are the weak link when the lubricant is interrupted. The SABP transmission has decreased vulnerability because of increased operating time after loss of lubricant since there are no planet bearings.

One SABP transmission with a 17.44:1 ratio is currently being tested in the 500-hp transmission facility at NASA Lewis, and another variant with a ratio of 101:1 is being fabricated for testing.

FUTURE PLANS

Rotorcraft for the 1990's and beyond require extremely light, long-lived, quiet drive systems. The NASA/Army research, together with the helicopter builders' careful designs, has provided reliable and strong drive systems for civilian and Army helicopters. This paper has reviewed significant research in drive systems and their components.

The critical issues are (1) to achieve significant advances in power-to-weight ratio, (2) to increase reliability, and (3) to reduce the transmission

noise. New concepts to achieve these goals have been investigated. The advanced 500-hp transmission has explored an increased power-to-weight ratio by using advanced design techniques, component improvements, and advanced materials. The value of this kind of research activity was realized during the upgrading of the Army's OH-58 helicopter to the D model, when the research on the advanced 500-hp transmission laid the ground work for the transmission in the D model. The bearingless planetary transmission with helical gears offers advantages in reliability and reduced noise. The split-torque concept offers significant weight savings for large-size helicopters.

Our plan for future NASA/Army transmission research calls for increased emphasis on noise reduction, an aggressive development of computer-aided design codes for transmissions, and the design and construction of demonstrator transmissions in large and small size categories (fig. 8).

An important new initiative in transmissions by the Army will be conducted through the Propulsion Directorate, Aviation Research and Technology Activity (ARTA). A 6-year program, beginning in 1987, will develop advanced concept demonstrator transmissions for two categories of helicopters: the Advanced Cargo Aircraft (ACA) and the Future Attack Rotorcraft (FAR). The program will parallel the concept offered by engine demonstrator programs, and provide a way for the industry to develop advanced concepts and trial designs well in advance of critical needs. This is a first time for such a program for transmissions.

The program will address the issues of weight, noise and reliability, reducing weight by 25 percent, reducing noise by 10 decibels, and increasing MTBR (mean time between removal) to 5000 hr. For the program to be successful, it depends on the continued Army/NASA expertise and cooperation at Lewis Research Center. The transmission program will build on the strong technology base from the joint NASA/Army programs as well as NASA's noise reduction research.

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REQUIREMENT	GOAL	BENEFIT
LIGHTER STRONGER	DRIVE TRAIN SPECIFIC WEIGHT 0.3 TO 0.5 lb/hp (CURRENTLY 0.4 TO 0.6 lb/hp)	INCREASED RANGE AND PAYLOAD
MORE RELIABLE	5000-hr MEAN TIME BETWEEN OVERHAULS (MTBO) (CURRENTLY 500 TO 2000 hrs)	LOWER OPERATING COST AND SAFER OPERATION
QUIETER	70 TO 80 dB IN CABIN (CURRENTLY 100 TO 110 dB)	GREATER USE FOR COMMERCIAL COMMUTER SERVICE INCREASED PASSENGER AND PILOT COMFORT

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Figure 1. - Transmission technology required for 1990's.

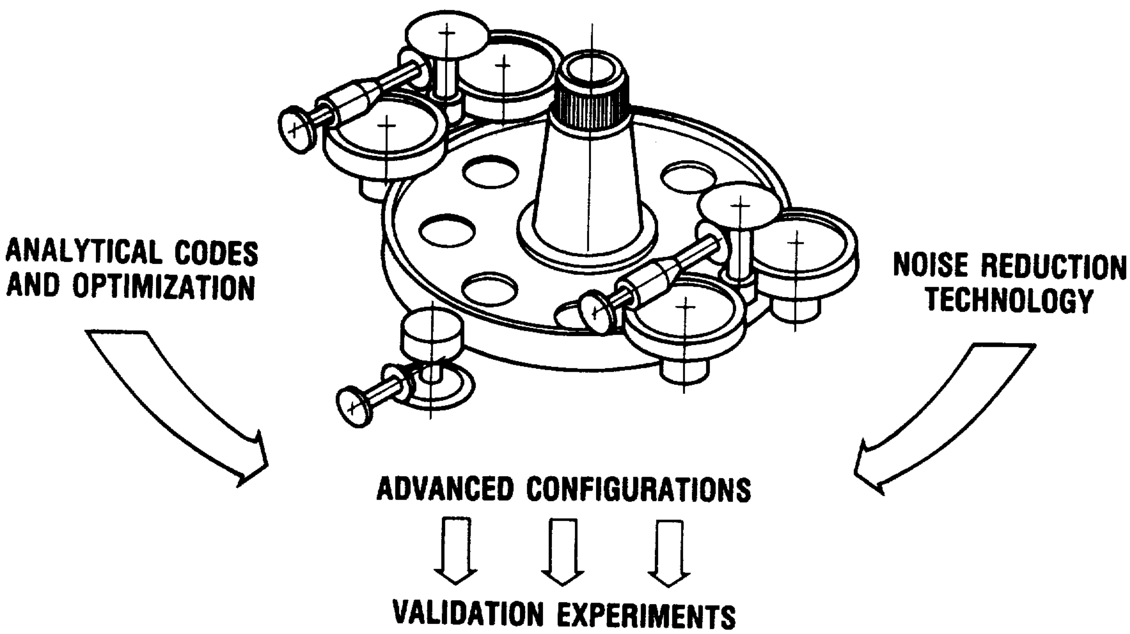

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Figure 2. - Current research activity in transmissions.

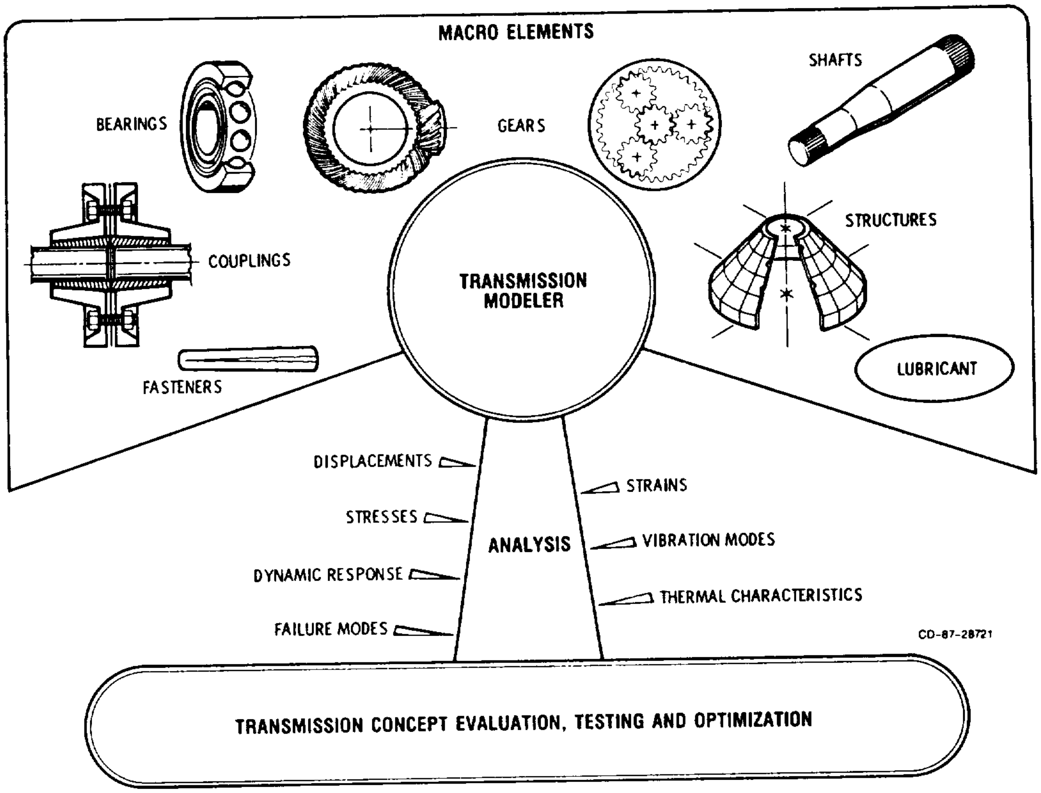


Figure 3. - Comprehensive transmission and modeling system.

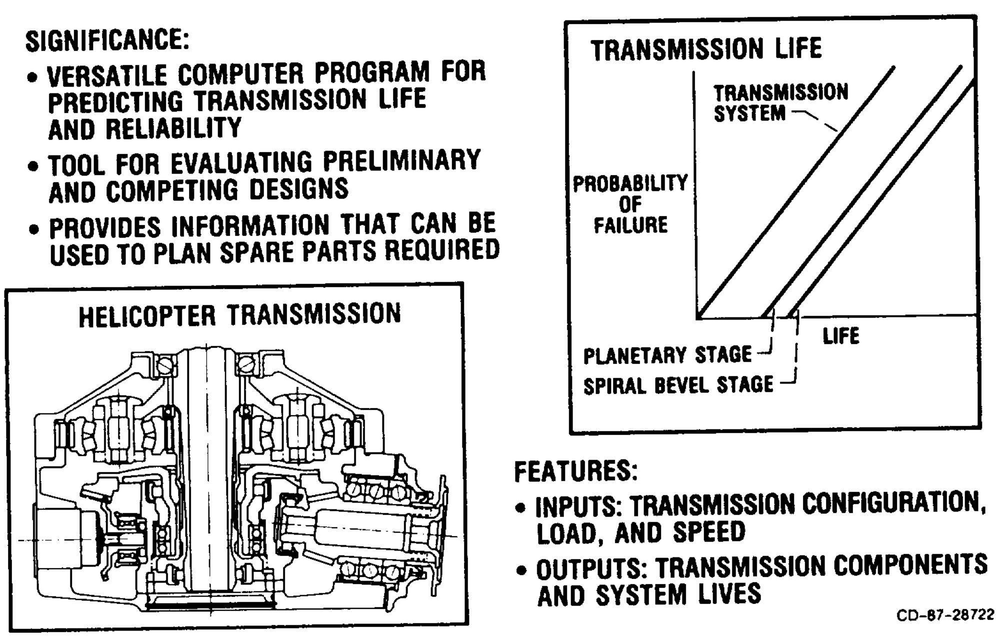


Figure 4. - Helicopter transmission life and reliability computer program.

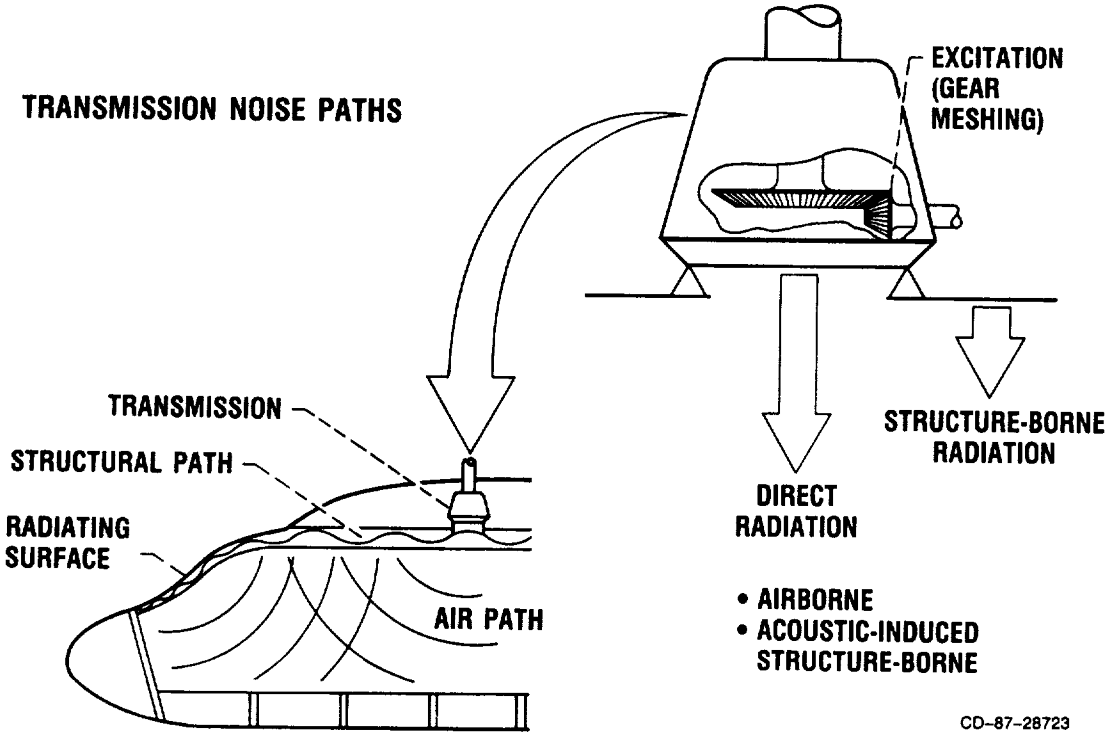
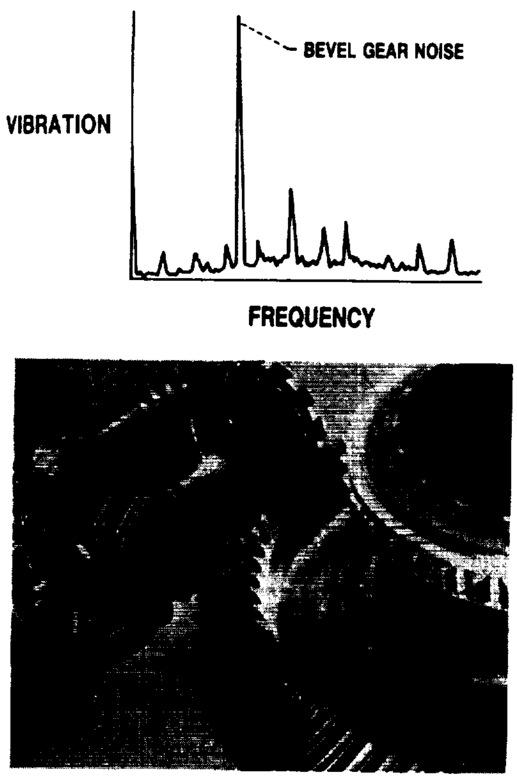


Figure 5. - Transmission noise reduction technology for rotorcraft.



SPIRAL BEVEL GEARS

MILESTONES COMPLETED:

- **MATHEMATICAL MODEL OF ZONE OF TOOTH CONTACT FOR SPIRAL BEVEL GEARS**
- **NEW UNDERSTANDING OF THREE-DIMENSIONAL NATURE OF TOOTH MESHING**
- **TIME AND FREQUENCY DOMAIN ANALYSIS FOR NOISE EXCITATION FUNCTION**
- **NASA CR 4081**

SIGNIFICANCE:

- **ALLOWS PREDICTION OF VIBRATION FROM GEAR MEASUREMENTS**
- **PROVIDES BASIS FOR FUTURE IMPROVEMENTS IN SPIRAL BEVEL GEAR DESIGN**

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Figure 6. - Spiral bevel gear noise modeling.

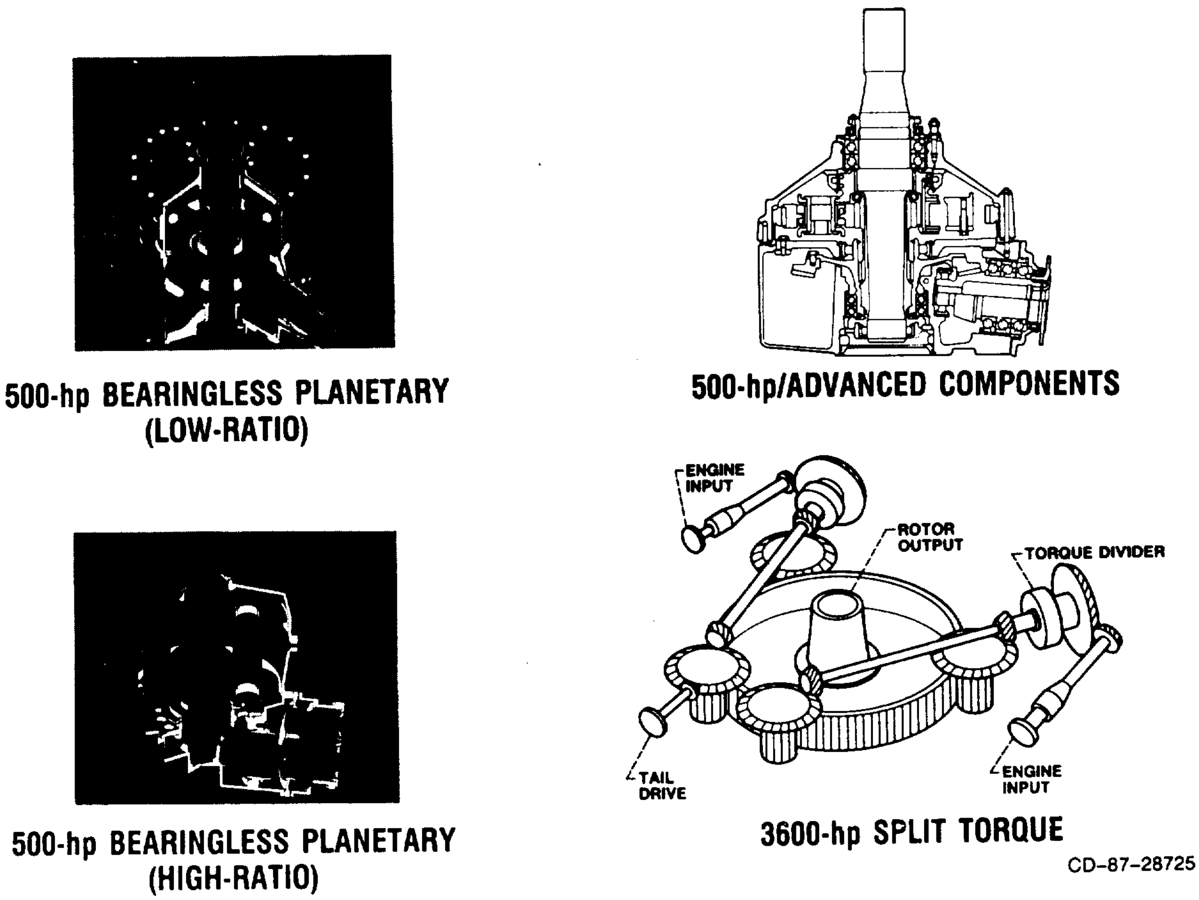

Figure 7. - Advanced transmissions.

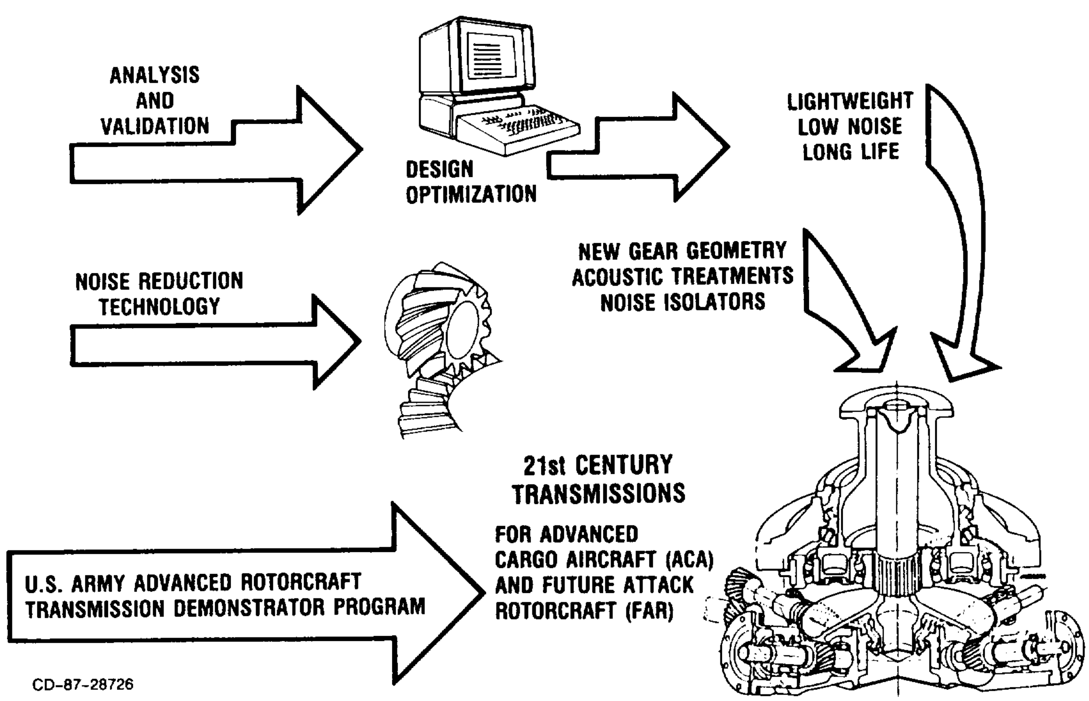

Figure 8. - Future thrust.